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CORONAS AND IRIDESCENT CLOUDS

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SYNOPSIS

Published observations and some new ones of coronas and iridescence are summarized to show (1) the essential facts about these diffraction phenomena, (2) the explanations for them, especially as to the limited part ice crystals may play in their formation, and (3) the relation between iridescence and cloud temperature.

Observations of coronas.—Coronas are the small colored rings frequently to be seen about the sun, moon, and, occasionally, bright stars or planets. The order of colors is such that blue is on the inside and red on the outside. Repetitions of the spectrum about the moon are observable, rarely, to a third red ring, but out from the sun at times brokenly to a fifth, and possibly a sixth or seventh red arc. Brilliant coronas can be observed in breath fog or on a befogged or frosted windowpane. The first red rings of coronas are most frequently from 1–5° from the sun or moon, but sizes down to 10′ from the edge of the moon, and up to 12° or 13° from the edge of the sun have been observed. Second rings, when seen beyond the first are usually at 70–100 per cent of the so-called radius, or distance of the first from the edge of the luminary. Third and fourth rings are commonly at irregular intervals greater than the radius of the first ring. Recognizable arcs of a fourth or fifth ring have been observed to about 30° from the sun, and of a second or third red ring to 11 or 12° from the moon. In about an eighth of the observations the corona is either distinctly noncircular or irregular, when cloud parts differing in stage of condensation or evaporation occur at the same angular distance from the luminary.

Observations of iridescence.—Iridescence on clouds is merely a mixture of portions of coronas of differing radii. Sometimes the mixture is regular, as in the banding parallel to the edge of a lenticular cloud. At others the mixture is irregular, as in the interior of a thin cloud of differing age or in wisps of fracto-cumulus. Iridescence may be seen about the moon at times to an angular distance of 12°, and about the sun to an angle of more than 57°, and even on the portion of the sky more or less opposite the sun. The brightest iridescences rarely extend to more than 30° from the sun. Lenticular clouds give the best displays, especially when they are forming and evaporating rapidly at low temperatures. As many as five spectra in succession, as marked by red bands, have been observed parallel to the rapidly forming edge of a lenticular cloud. Iridescence on fracto-cumulus wisps, while showing a connection with the rapidity of cloud formation and evaporation, is distinctly related to the temperature of the cloud. Extended brilliant iridescences occur only when the temperatures of this type of cloud are below about −5° C. A study of 38 cases showed that when iridescence extended to 20° or less from the sun the computed average cloud temperature was 3° C. and in no instance below −7° C.; when colors were visible to more than 20° but not over 30° the average was 0° C. and the coldest −13° C.; with coloring out more than 30° but not over 40° the average was −10° C. and the coldest −18° C., while with colors to more than 40° the average was −15° C. and the lowest −21° C. Iridescence on windowpanes covered with ice plates of frozen dew is of a different nature from the cloud iridescence.

Cause of coronas and iridescence.—Diffraction of light by small particles is the evident cause of coronas and iridescence. It seems probable that the particles involved are almost invariably water droplets, for the following reasons: (1) Brilliant coronas, glories, and iridescence have been observed on clouds known to be composed of water droplets, and, it seems, not on clouds known to have been exclusively of ice. (2) The most brilliant and widespread iridescence occurs on clouds forming and evaporating with a rapidity probably not possible for aggregates of ice crystals at temperatures so low as those where these clouds occur. (3) Liquid droplets have been observed at temperatures as low as those of most, if not all, iridescent clouds. Under rapid condensation at low temperatures such droplets seem more likely to form than ice crystals. Crystals, however, begin to form in such clouds of liquid droplets very soon, for lenticular iridescent clouds often transform quickly into distinctly different, noniridescent, sometimes halo-producing clouds of falling snow. (4) An analysis of the sizes of double, triple, and quadruple coronas gives no evidence that any were formed by ice crystals, and shows definitely that in all but a very small percentage of cases ice spicules could not have been the cause. Only in the case of the small, nearly colorless annuli almost invariably seen in conjunction with halos on the same cirro-stratus clouds, do ice crystal clouds appear to form coronas, except in rare instances.

The observation of a colored solar corona on a windowpane covered with small spicules, shows that the lack of positive evidence of colored coronas due to ice spicule clouds can not definitely exclude the possibility of their occurrence. Furthermore, a small, colored triple corona was once observed on a cloud apparently of tabular crystals.

Iridescence and coronas as guides to cloud temperature and, therefore, cloud height.—If, as seems established, coronas and iridescence indicate water clouds, and if, as appears reasonable, we assume that clouds of liquid droplets do not, except for very brief periods, occur at temperatures lower than the lowest at which liquid droplets have been observed, iridescent or corona-forming clouds may be correctly considered as having a temperature not lower than −35° C. Since the lower the temperature the more brilliant and extensive the iridescence and coronas, brilliance and angular extent of color may be used as a rough guide to the temperature, on the basis of observations made on fracto-cumulus clouds at computed temperatures. Once the temperature of the cloud is approximated the height may be estimated with the aid of the probable lapse rate in temperature at the time. Coronas and iridescence because of this relation to temperature should be observed as regularly as halos, and may be used as a criterion in distinguishing "alto-" from "cirro"-clouds.

INTRODUCTION

With dark glasses or a black mirror nephoscope at hand an observer may become acquainted with the beauties of the frequently occurring coronas and the less common iridescence near the sun or moon. Numerous observers have published descriptions of these beautiful phenomena and not a few have attempted explanations as well. The essentials of some of the published information and some details of a new series of observations will here be presented and discussed.

OBSERVATIONS OF CORONAS

Description of coronas.—Coronas are most readily seen about the moon, for here the light is not blinding. Near the moon there is a whitish area often with a ring of bluish tinge a short distance out, which grades into an orange-red ring still farther away. Often there is violet or purple and at times a further run of color through blue, green, yellow, orange, and red, with increasing distance from the moon. Still a third spectral series of rings is rarely seen. Around the brighter sun the more intense light occasionally gives as many as four spectral series. There appears to be no record of five series in complete rings having been seen at once, though five, six, or seven partial ones have been observed. The outermost series are usually mostly only diffuse greens and reds. Small, generally faint coronas are sometimes observed about a bright planet or star. Beautiful coronas are best seen on sheet clouds or thin fogs. Even with the passage of frayed clouds or wisps of fog, fleeting portions of coronas occur. Brilliant coronas can be observed in steam or breath fog or on a befogged or frosted windowpane.

* This paper was completed and first submitted on July 25, 1923. It has since been considerably shortened and slightly revised.—C. F. B.

Angular sizes of coronas.—On clouds the radius of the first red ring of a corona is most frequently about 1–5°. Occasionally it is less than ⅔° or more than 10°. The following table shows the frequency of coronas of different sizes in 132 measurements (mostly at Ben Nevis, Scotland) presented by Pernter,[1] and 164 noninstrumental observations of my own at Urbana, Ill., October, 1907–April, 1908, and at Worcester, Mass, November 1921,–June, 1923:

TABLE 1.—*Frequencies of angular sizes of coronas*

Radius of first red ring	0–1/2°	1/2–1°	1–2°	2–3°	3–4°	4–5°	5–6°	6–7°	7–8°	8–9°	9–10°	Total
From Pernter and Exner	0	5	43.5	52.5	21.5	8.5	1	0	0	0	0	132
Urbana, Ill	7	7	3	7	6	10	1	2	0	1	0	44
Worcester, Mass	10	9	10	20	23	25	14	5	2	1	3	122
Totals	17	21	56.5	79.5	50.5	43.5	16	7	2	2	3	298

The observations cited by Pernter were made with great care, and stated to the nearest minute of arc. Those made by Brooks were done roughly by estimation (Urbana) and by crude angular measurement to the nearest whole or half degree, with pencil or index finger at arm's length. The Worcester observations include seven instances of radii varying by 2, 3, 4, 5, or 6° within the same cloud. In each case these are put with the class showing the smallest of the observed radii, e. g., the observations of radii varying from 4–6° is classed with others of 4–5°.

TABLE 2.—*Occurrences of markedly noncircular coronas*

Radii	2–4°	3–8°	3–9°	3-1/2–10?°	4–6°	4–7°	4–9°	5–8°	9–13(?)°	Total
On lenticular clouds	1	1	1	1	2	1	1	1	1	10

Radii	3–7°	3–8°	4–9°	5–9°	6–9°	7–10°	7–12(?)°	
On fracto-cumulus clouds	1	1	1	1	1	1	1	7

The smallest corona measured at Worcester was 10′ to the first red ring, and the largest (only one observation) 13°. At distances of less than ½° from the edge of the luminary, except in the case of bright planets or stars, the ring becomes narrow and its coloring faint. Such very small coronas about the moon are called lunar annuli, and are almost invariably associated with halos in the same cloud. When the moon is not full, the corona, particularly when small, is not circular, but flattened on the side where the moon is flattened. The first condensation on a windowpane, e. g, when a cold wind springs up outside, may give a corona of 8° radius to the first red ring. One's breath fog in the open gives nearly the same, 7–9° to the first, and (once accompanying a 9° inner red ring) 16° to the second, red ring.

Anglar distances of second rings beyond the first.—In double coronas the second red ring usually occurs at a slightly less distance from the first red ring than that ring is from the edge of the luminary, as shown in table 3:

TABLE 3.—*Angular radius of second red ring in percentage of angular radius of the first*

Per cent	140–150	151–161	162–172	173–183	184–194	195–205	206–216	217–227	228–238	239–249	Over 250	Total
Kämtz	0	0	2	4	4	1	0	0	0	0	0	11
Ben Nevis (summer)	3	2	2	0	3	7	2	3	1	2	1	26
Ben Nevis (winter)	0	1	2	3	3.5	7.5	0	0	2	0	0	19
Brooks	1	1	5	15	1	4	1	1	1	1	5	36
All observations	4	4	11	22	11.5	19.5	3	4	4	3	6	92

[1] J. M. Pernter and F. M. Exner, Meteorologische Optik, 2nd ed., pp. 504–506, Wien and Leipzig, 1922.

The data here presented were compiled from observations collected by Kämtz and some made at Ben Nevis Observatory, and presented in Pernter's Meteorologische Optik,[2] and from observations made by Brooks at Urbana, Ill. (6 cases), Washington, D. C. (1 case), and Worcester, Mass. (29 cases). (First published herewith.)

Sizes of triple and quadruple coronas.—Pertner includes 10 instances in which third red rings were measured, and 2 in which there were fourth rings as well. Brooks' observations include 15 measurements of a third ring, 2 of a fourth ring and 1 of a portion of a fifth, as in Table 4:

TABLE 4.—*Angular measurements of red rings (in degrees and minutes from edge of sun or moon) for triple to quintuple coronas*

Red rings, cited by Pernter				Red rings, Brooks' observations				
First	Second	Third	Fourth	First	Second	Third	Fourth	Fifth
° ′	° ′	° ′	° ′	°	°	°	°	°
2 3	3 1	4 5	--------	¼	1¾	3¼	--------	--------
1 10	3 46	6 18	7 22	¾	2¼	4¼	--------	--------
1 23	2 52	3 36	--------	1¼	2¼	3¾	--------	--------
1 43	2 35	4 24	--------	4	6	9	--------	--------
1 28	2 26	3 54	--------	2.5–4	4–6	6–9	--------	--------
2 23	4 30	7 39	9 25	5	9	11.5	18	28
1 5	1 55	2 55	--------	5	9	12	--------	--------
1 22	2 5	4 23	--------	¾	1½	3	--------	--------
0 57	1 48	3 25	--------	5–8	9–11	13–18	25–27	--------
--------	2 25	4 30	--------	4–5	7–9	10–11	--------	--------
				7	(9–)12	16	--------	--------
				4–5	7–9	13a	--------	--------
				3½	6	9	--------	--------
				3–5–9	9–13	13	--------	--------
				1	2–4	6	--------	--------

The first three of Brooks' observations are from estimated diameters from which ½°, the diameter of the sun or moon, has been subtracted before dividing by 2 to get the radius. Among the others, where more than one angle is given for a single ring, the ring was of different radii in different directions.

Noncircular or irregular coronas.—Mention has been made above and Table 2 presented, showing that coronas markedly noncircular have been observed about one time in seven, on the average. Such coronas are most noticeable on clouds in which the different portions vary appreciably in age and, therefore, in size of particles. Sometimes when a smooth cloud with thickness gradually increasing toward the interior drifts in front of the moon or sun the corona is found to present the appearance of a parabola or hyperbola, open to the edge of the cloud and standing nearest the sun or moon where the cloud is densest. If the cloud is not smooth the corona is observed to have an irregular radius, as on wisps of fracto-cumulus clouds. The greatest departures from circular coronas, attaining at times 300 per cent of the distance of the nearest portion of the first red ring, occur with the most rapidly forming and evaporating clouds, for on the thin edges the droplets are so small that the red is diffracted to a large angle, while toward the interior, where the droplets have been growing for a short time, the diffraction is to an appreciably smaller angle (cf. Table 8, below). To observe a noncircular corona it is not necessary to wait till such a cloud is seen, for it can be viewed on a partially befogged or finely frosted window pane almost any cool evening. When such noncircular coronas are visible there is often much more or less irregular coloring out to considerable angular distances from the center of light.

OBSERVATIONS OF IRIDESCENCE

Perhaps the earliest full account of iridescent clouds, showing their relation to coronas and including a satis-

[2] Ibid.

factory explanation of the nature of the color, is that by Sir John F. W. Herschel, published in 1862.[3] Since Herschel's time, iridescence on clouds, usually associated with bright coronas, has been observed and described by many, but few have undertaken systematic observations. Hildebrandsson, Mohn, McConnel, Carlheim-Gyllenskiöld, Schips, and Arendt have provided the best series of observations.[4] Scattered observations are available in various meteorological books and journals and at times in general science journals.[5] These all deal with observations in sunlight. Moonlight is generally too weak to produce this effect. Brooks has seen more or less lenticular iridescent clouds in moonlight only twice and to a maximum of 12° from the moon. Three out of seventy-one observations of iridescent clouds at Upsala, 1866–1892, were in moonlight.[6] In sunlight iridescence may be brightly developed, usually showing bands of color hemming the edges of the clouds but having a tendency to be more or less concentric about the sun. Near the sun, coronas and this iridescence merge into one another in such a manner that it is evident they are of the same nature. Since iridescence usually occurs only on rapidly forming or evaporating clouds, it is usually seen with the change of wind on the approach of a storm or just after the wind shifts and the sky begins to clear as a storm passes on. The cold, boisterous winds on the rear of a cyclone are especially favorable to the development of iridescent fracto-cumulus and strato-cumulus clouds and higher, lenticular clouds.[7]

Some unusual displays of coronas and iridescence.—In 1922 and 1923, at Worcester, Mass., I observed four truly magnificent displays of solar coronas and accompanying iridescent clouds. In some respects these excelled even the wonderful occurrence described by Herschel. Brief summaries of these brilliant occurrences will, therefore, it is hoped, be worthwhile additions to data already published. Again and again I have seen one portion or another of such displays almost duplicated. The essentials of these four displays are: [8]

Those of November 29, 1922, and November 25, 1923, were noteworthy, because of the rapidity with which the clouds were forming and the colors changing, for the occurrence of five spectral series paralleling the edge of a cloud, in each case, and for the rapidity of the disintegration of the denser parts of the cloud into falling snow.

The iridescence of December 19, 1922, was notable for the extreme brilliance of the color over large areas, for the extent of visible colors through six or seven spectra out from the sun, and for the extent of the iridescence to 40° and 45° from the sun on clouds of two levels at the same time.

The display of February 25, 1923, was particularly interesting because of the successive presentation of beautiful coronas and iridescence on clouds at three levels; because of the well-marked triple corona with red rings at successive equal distances from the sun and with a weak sun pillar and lateral portion of a 22° solar halo or parhelion in the same (?) cloud at almost the same time; because of the marked difference in the radii of the corona on a lenticular cloud along the edge, vs. toward the center, and because of a similar diversity between the coronal radii in different parts of cumulus wisps.

[3] Sir John F. W. Herschel, Meteorology, London, 1862, 2nd ed., pp. 224–225.

[4] Th. Arendt, Irisirende Wolken, *Das Wetter*, Oct. and Nov., 1897, 14: 217–224, 244–252. A bibliographic summary of data available at that time.

[5] E. g. *Nature* (London), see "Iridescent clouds" in the indexes for vols. 31 (1885–86), esp. letter by C. Davison, in issue for Jan. 28, 1886, pp. 292–293, 2 figs., 33 (1886–87), esp. letter by T. W. Backhouse, in issue for Mar. 25, 1886, p. 486, describing iridescent clouds roughly triangulated at a height of 11–23 miles, 35 (1887–88), esp. J. C. McConnel, p. 533 and G. H. Stone, p. 581, the latter describing brilliant and extended iridescence at Colorado Springs, Colo., during chinook. An unusual display is described in *Science* (N. Y.), Mar. 10, 1922, N. S. 55:263.

[6] *Met. Zeitschr.*, 12:72, 1895.

[7] Cf. Arendt, loc. cit., pp. 247–248.

[8] The detailed descriptions have been placed on file in the libraries of the U. S. Weather Bureau, Washington, D. C., the British Meteorological Office, London, England, and the Prussian Meteorological Institute, Berlin, Germany.

Frequency of iridescence.—Most people being unequipped with dark glasses are not accustomed to looking up, and so never see these wonderful color effects. But he who will carry dark glasses can often view the unannounced color marvels of the sky. While the phenomenon in such brilliant form as here described for a number of instances is rare, nevertheless iridescence on clouds is a common, and, as McConnel agrees,[9] almost daily occurrence during some periods in winter.

Arendt in his bibliographic summary of observations of iridescent clouds [10] likewise shows that the phenomenon is of frequent occurrence, though the frequency of observation seems to depend largely on the observer. Thirty-six observations by Carlheim-Gyllenskiöld, 97 (including some of coronas only) by Schips (2 years), 42 by Mohn (22 years), 71 cited by Hildebrandsson (27 years) and 65 by Arendt (5 years) are discussed. Schips' observations showed 56 days with coronas or iridescent clouds in two years. From November, 1922, to October, 1923, I observed iridescence in 142 instances on 99 days. Iridescence was observed fourteen times on two or three well-defined levels of cloud simultaneously. Most of these, or 77 cases on 49 days, were during the cold, snowy months December to March, inclusive:

TABLE 5.—*Observations of iridescence by C. F. Brooks, November, 1922, to October, 1923*

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Total
Cases	10	14	13	33	16	10	3	9	10	12	4	8	142
Days	7	10	11	16	12	9	3	4	9	8	3	6	99

February was a particularly cold month, with light snowfall practically every day. Forest fire smoke in May and June, as well as the spending of less time in observing, limited the cases cited. While Schips' observations [11] show the four warmest (brightest) hours winter and summer to be those with the most frequent occurrence, I hesitate to classify my observations by hours, for the times I observed were usually between 8 and 9 a. m. and 1 and 3 p. m. I made no attempt to watch the sky at times other than when I happened to be outdoors, which was an average of about one hour per day. On the whole, I observed iridescence about two-thirds as often as coronas.

Angular extent of iridescence.—One feature not often mentioned in descriptions of iridescent clouds is the observation of these colors to angles exceeding 23°, the outermost limit reported by McConnel in his early article.[12] In my observations I have *usually* detected iridescence beyond 23°. In fact, it was not uncommon to see the pinkish or reddish hems of greenish clouds more than 40° from the sun and on several occasions to more than 50°:

TABLE 6.—*Angular extent of (solar) iridescence observed by C. F. Brooks*

Outer limit	5–10°	11–20°	21–30°	31–40°	41–50°	51–60°	Over 60°*	Total
Cases	†20–	27–	46	28	11	4	5	136

* Red tinge only.

† More consistent observations, with dark glasses, would probably make these figures far in excess of the others.

In some cases, especially in those showing the smaller angles, the actual limit of iridescence might have been greater had there been clouds in the right positions to show it. The extreme limit to which I am sure of both

[9] J. C. McConnel, on the causes of iridescence in clouds, *Phil. Mag.*, 5th ser., 1887 **24**, 423; 1890, **29**, 168–169.

[10] Arendt, loc. cit.

[11] Summarized by Arendt, ibid., pp. 246–247.

[12] Loc. cit., pp. 423–424.

red and green tints is over 57° (April 19, 1923), while for red alone it is 124° from the sun (January 26, 1924). I observed two colors out to 55° on July 26, 1920, at Washington, D. C.,[13] and on February 23, 1923, at Worcester, Mass. At least two other American observers have reported iridescence out to 45° or more from the sun. G. H. Stone's description of iridescent lenticular clouds observed at Colorado Springs, Colo., during a chinook, indicating great brilliance of color, and distribution from 5 to more than 45° from the sun, shows that his observation equalled in brilliance anything I have seen.[14] Mabel A. Chase recently reported a brilliant display of iridescent clouds in which the coloring extended to 45° from the sun,[15] while C. Bonacini has just published an account of fine iridescence, like a web of silk threads of different colors, observed to 70° and more of angular distance from the man.[16]

McConnel, in the winter following the publication of his first article, observed iridescence on four occasions to more than 23°, the farthest being 37°.[17] He refers also to [18] unusually vivid iridescence seen in England and Scotland during the winters 1884–85 and 1885–86, described in a number of letters to *Nature*. Colors were visible on these at less than 50° and more than 130° from the sun (coronal and glory colors, respectively, each within 50° of the sun and a point directly opposite, i.e., 180° away). McConnel says these clouds seem to have been of a special type, and that one was found to be at least 11 miles high. It would probably be worth while on occasions of brilliant and extensive iridescence, about the sun, to examine clouds for iridescence at angles exceeding 130° from the sun.

Extent of iridescence on fracto-cumulus clouds at different temperatures.—Observations of diffraction colors on fracto-cumulus clouds at different temperatures are classified in the following table:

TABLE 7.—*Diffraction colors on fracto-cumulus clouds at different temperatures*

Extent of iridescence from sun	Number of cases	Computed cloud temperatures [1] (individual cases)	Computed cloud temperature		
			Average	Lowest	Highest
		°C.	°C.	°C.	°C.
10–20°	7	−7, −6, −4(h), −4(h), −2, 6, 14	[2]3	−7	14
20–30°	12	−13, −8(h), −7, −3, −2, 0(d), 2(h), 4, 6, 6, 7, 10.	0	−13	10
30–40°	13	−18, −18(h), −17(h), −16(dp), −14, −11(ph), −10, −8(d), −6, −6, −1, 3, 3(h).	−9	−18	3
Over 40°	7	−22(h), −20, −18(h), −18(s), −11(h), −10, −7(h).	−15	−22	−7
Total	39	(distributed by months as follows: Dec., 3; Jan., 3; Feb., 11; Mar., 5; Apr., 1; May, 1; June, 3; July, 1; Aug., 2; Sept., 4; Oct., 5.)			

[1] The cloud temperature was computed from the following approximate formula: $t_c = t_d - 0.2\,(t_a - t_d)/\,0.77$, in which t_c, t_d, and t_a are, respectively, the cloud base temperature, the dewpoint at the ground, and the air temperature at the ground, all in °C. For this formula the dewpoint was obtained with dew-point hygrometer in the case of observations marked (dp) with hair hygrometer (h), or with sling psychrometer (p or no letter). In one instance the cloud height was obtained by triangulation with the aid of the cloud shadow at known distance, and the temperature was then computed at an assumed lapse rate of 1.0° C. per 100 m.

[2] This average is not strictly comparable with the others, as observations at less than 20° were not attempted for July-October.

[13] C. F. Brooks, Iridescent Clouds, *Mo. Weather Rev.*, June, 1920, **48**: 333, ft. note.

[14] G. H. Stone, Iridescent clouds, *Nature*, Apr. 21, 1887, **35**:580.

[15] Mabel A. Chase, Iridescent clouds, *Science*, Mar. 30, 1922, N. S. **55**:263.

[16] C. Bonacini, Nubi iridate, *Boll. Bimensuale Soc. Met. Ital.*, 1924, **44**:73–74. The whole paper, pp. 71–78, extracts from a longer one, presents some other observations on iridescent clouds, mentions the scarcity of recorded observations of the sort in Italy, and attempts to place iridescence in a different category from coronas by offering to explain iridescence as the result of supposed fine striations on laminar crystals of which the author assumes iridescent clouds must be composed. (I am indebted to Miss E. C. H. Brooks for translating this paper.—C. F. B.)

[17] J. C. McConnel, On diffraction colors, with special reference to coronae and iridescent clouds, *Phil. Mag.*, 5th ser., **29**:168.

[18] Ibid., p. 170.

The data presented in this table appear reasonably accurate, notwithstanding three minor sources of error: (1) Observing the angular extent of iridescence, (2) determining the dew point, and (3) obtaining the cloud temperature. The angular observations of iridescence depend not only on distinguishing the colors, but also on clouds being at distances such that the limit may be established. In the case of fracto-cumulus clouds, the number of units and their motion allows fairly readily the determination of the angular limits of iridescence, probably correct to within 5°. Determining the dew point in cold weather is always difficult. During the months December, 1922, to October, 1923, when these observations were made, I took almost daily observations with the sling psychrometer, and in the cold weather of December and January supplemented these with determinations of the dew point with a table-salt and snow mixture in a silver or bright aluminum cup. Throughout the period a hair hygrograph was in operation. The dew-point observations made with the dew-point hygrometer and the psychrometer at wet-bulb temperatures above 0° C. may be considered accurate within 0.5° C., those with the psychrometer below 0° C., within 1° C., and those obtained from the hair hygrograph, correct within 1.5° C. The temperature at which air ascending from the ground would reach saturation has been taken as the probable cloud temperature. This assumption is open to errors which are known to be generally small. Clayton [19] has compared observed heights of cumulus clouds with those computed by the dewpoint formula and found the computed heights lower (−) or higher (+) by the following number of meters in 10 instances: +55, −42, −12, +104, +42, −4, +35, −14, −133, and −5. The average difference is ±45 m., which under adiabatic conditions, corresponds to an average error of 0.5° C. Thus, it seems safe to assume that the cloud temperatures indicated are probably correct to within 1° C. in 17 instances, to within 1.5° C. in 10 more, and to within 2° C. in 11 more. The remaining case, in which the cloud height was obtained, with the aid of its shadow, by rough triangulation, is probably not more than 1° C. in error. As the most extended iridescence is unusually observed on forming cumulus wisps, the temperatures of the cloud bases reasonably approximate those of the clouds on which the iridescence is observed.

Accepting Table 7 as it stands, it is noteworthy that both the average and extreme temperatures are lowest for the most extended iridescences and highest for the least extended, and that there is an orderly gradation between. Owing to the large range of cloud temperature, 15 to 23° C., within each group it is evident that further observations are required before any averages can be dependable within a degree or two.

A closer relationship between extent of iridescence and computed cloud temperature seems to be prevented by the varying intensity of convection. The more rapidly the clouds are forming, that is, the more intense the convection, the greater are the cloud areas with droplets sufficiently alike in size to make the colors stand out plainly. Therefore, the more intense the convection, cloud temperatures being equal, the more extended the iridescence is likely to be. Nevertheless, this factor is not sufficient to obscure well marked changes in the extent of iridescence accompanying appreciable changes of cloud temperature on any day. Four instances may be cited of the usual increase in the angular extent of

[19] H. H. Clayton, World Weather, Table XI, p. 162, New York, 1923.

iridescence with falling cloud temperature from morning to afternoon: December 13, 1922, February 10, 18, and June 27, 1923. The observations on December 13 showed a greater brilliance of iridescence in the afternoon than in the morning, the computed cloud temperature having fallen from $-14°$ to $-18°$ C. The observations on February 10 showed an extent of iridescence increasing from 15° at 1:05 p. m., when the cloud temperature was probably $-4°$ C., to 22° at 1:30 p. m., when the cloud temperature had fallen to $-7°$ C. On February 18, while there seems to have been no change in cloud temperature, which was probably $-18°$ C. at 9 a. m. and 11:40 a. m., the iridescence spread from 30° at the earlier hour, to 40° with reddish tints visible to 50° out, at the later observation. Here the spread was apparently owing to increased intensity of convection. On June 27 the iridescence extended to 20° at 6:30 a. m., but to 30° at 1:20 p. m. The computed cloud tempertures fell from 14° to 10° C. in this period. At both observations there was considerable turbulence in the 25 mi./hr. west wind. On August 22 the iridescence increased from 25° to 28° out from the sun from 12 to 4 p. m., during a dry, colder and colder gale. September 30, 1923, there was an instance of decreasing radius of iridescence with rising cloud temperature as a hurricane drew near. About 11:30 to 12, angular limits of 32, 35, 35, 38, and 38° were observed, the computed cloud temperature being about 3° C., while at 2 p. m. 25° was the limit, the computed cloud temperature being 4° C. Though some of the observations do not fall well into line, it appears that a change of about 3° C. in cloud temperature is sufficient to change the extent of iridescence by 10°.

At low temperatures cumulus clouds are ephemeral, quickly transforming into clouds of falling snow. At temperatures much below $-20°$ C. the change is so rapid that iridescence is too fleeting to be extensively observable at one time, unless new clouds are continually forming in large numbers. At temperatures above 5° C. condensation of the more abundant supply of water vapor so quickly results in numbers of droplets larger than the very small size (about 0.005 mm. diameter) which best form extensive iridescences, that these colorings are rarely to be seen more than 20° from the sun. Obviously, at temperatures between about $-20°$ C. and 5° C. the clouds are neither too ephemeral nor composed of droplets too large to provide extensive iridescence.

Summary.—The observations presented show that coronas are more or less concentric rings of color in spectral successions at moderate angular distances from the sun. Iridescence, however, is a bright to faint coloring from any part of the spectrum, in irregular splotches or in bands paralleling the edge of a cloud. With movement toward or from the sun the colors of particular cloudlets change as they move through the more or less fixed zones of potential color for the sizes of the cloud particles. On near approach of an iridescent cloud to the sun the colors take on a more or less circular arrangement, with a red ring at a certain minimum radius. Iridescent coloring has been noted on several occasions by different observers to an angular distance of 45° from the sun. The brilliance, however, usually fades rapidly beyond a distance of 20° or 30°.

Windowpane iridescence.—Color bands suggestive of those on the edges of clouds may be seen on windowpanes covered with frozen fine dew. These, however, are separated from the corona by a colorless zone, and the arrangement of colors is the reverse of that in the corona. Unlike iridescence on clouds, such bands are, evidently, produced by the interference of transmitted light with that transmitted and doubly reflected from the opposite faces of the thin plates of ice, held in parallel orientation on the windowpane. One cold morning when there was frozen dew and a new deposit of frost on different parts of the same windowpane, solar coronas could be seen on both, but the noncircular color bands on the deposit of frozen dew only.[20]

CAUSE OF CORONAS AND IRIDESCENCE

The explanation [21] for these beautiful colors on clouds, is that they are owing to interference in diffraction of light. So far as clouds are concerned, coronas and iridescence are probably due only to diffraction by very small particles. In passing through the spaces between the particles the light waves spread as from new sources, with convex wave fronts. The waves from the different spaces cross, and, in consequence, make alternating zones of double illumination and darkness. Each wave length has its own sets of wave fronts, which on interfering produce bright and dark bands at different angular distances from the source of light. Thus the bright phase of one color occurs in the dark phase of another, and this leads to rings of colored light at certain angles from the luminary. As the wave fronts of the light of shorter wave lengths, e. g., blue, are least diffracted in passing through a dusty or cloudy medium, the color seen nearest the sun or moon is bluish, and is followed in succession by green, yellow, orange, and red. Then there is another series marking the second zones of reinforcement of the several colors—violet, indigo, blue, green, yellow, orange, and red. The size of the innermost red ring, and, of course, of all the others, too, is dependent on the size of the particles causing the diffraction. The smaller the ring the larger are the particles making it. This relation between the radius of the first red ring and the diameter of the diffracting spheres is given by the following formula:[22]

$$\sin r = .00082/d,$$

in which r is the angular distance of the first red ring from the edge of the luminary, 0.00082 a constant for the first red ring (n [=1]+0.22) 0.000671 [the wave length of red, in mm.], and d the diameter of the droplets (in mm.) responsible for the red ring of radius r. The following table is derived from this formula:

TABLE 8.—*Relation of radius of first red ring of corona (r) to diameter of droplets (d)*

r	0°10′	0°20′	0°30′	1°	1°30′	2°	3°	4°	5°	6°	°8	10°	12°
d (in mm.)	0.282	0.141	0.094	0.047	0.031	0.023	0.016	0.012	0.009	0.008	0.006	0.005	0.004

From the radius of the chestnut-brown corona Richardson has just shown [23] that

$$(\text{diameter of obstacle}) = \frac{5.3 \times 10^{-5}\ \text{cm.}}{\left\{\begin{array}{c}\text{(radius of chestnut-brown}\\ \text{corona) minus}\\ \tfrac{1}{2}\ \textit{(radius of source).}\end{array}\right\}}$$

[20] For details concerning interference of light see books on physics, or the Encyclopedia Britannica, 11th ed., vol. 14, pp. 685–693 (Interference of light), and vol. 8, pp. 238–255 (Diffraction of light).

[21] For details on diffraction by water droplets see W. J. Humphreys, Physics of the Air, Philadelphia, 1920, pp. 528–536, and on diffraction by ice spicules see J. C. McConnel, On diffraction colors, with special reference to coronae and iridescent clouds, *Phil. Mag.*, 28: 272–289, 1889, 29: 167–173, 1890.

[22] Derived from that presented in Humphreys, op. cit., p. 534.

[23] L. F. Richardson, The brown corona and the diameter of particles, *Quar. Jour. Roy. Met'l. Soc.*, Jan., 1925, 51: 1–6.

From this formula, applicable for droplet diameters of ordinary size, 5 to 20 microns, Table 8 b has been computed.

TABLE 8 b.—*Relation of radius of chestnut-brown ring (r) to diameter of droplets (d)*

r	1° 40′	2°	3°	4°	5°	6°
d (in mm.)	0.020	0.016	0.010	0.008	0.006	0.005

Iridescence on clouds, as already described, seems to be merely a mixture of coronas of different radii resulting from the particles being of different sizes in different portions of the cloud at the same angular distance from the sun or moon.

History and criticism of theories as to the cause of coronas and irridescence.—So far as is known, the formation of coronas and irridescent colors on clouds, as just explained, can take place only as the result of interference of light of different wave lengths as it is diffracted in passing minute particles. Snow crystals are unequal in their several dimensions, and oriented more or less fortuitously. Thus, even when the crystals are sufficiently small to make a corona large enough to be seen, their irregularity of form and orientation should so diffuse the diffraction pattern as to render it practically, if not quite, invisible. When interference colors are seen on clouds, it is presumed, therefore, as must usually be the case, that the particles involved are liquid droplets. The occurrence of such clouds in the air at temperatures far below the usual freezing point of water presents no difficulty, for clouds or fogs of liquid droplets have been observed at temperatures down to −34.5° C., as will be noted below. Why liquid droplets form and do not freeze at such low temperatures is not known.

The similarity of iridescence on clouds to iridescent films led Stoney[24] to suggest that this coloration was caused by interference of light reflected from the opposite faces of thin, transparent plates of ice. McConnel[25] with numerous personal observations[26] at his command, immediately pointed out objections fatal to Stoney's hypothesis. His own generally excellent discussion (1887) was marred, however, by the unnecessary assumption that all high, and therefore cold, clouds must be of ice and, consequently, that most of the iridescence he had seen on clouds had to be explained as the result of the diffractive effect of ice spicules.[27] Nevertheless, his detailed mathematical discussion of coronas includes both spicular and water-droplet kinds. Pernter[28] accepted McConnel's theory, and assumed that all the larger and brighter coronas must be caused by ice spicules, for at the large angles to which iridescence was observed the intensity of light diffracted by water droplets would not be nearly so great as that from ice spicules. Simpson[29] questioned several of Pernter's explanations and brought a new point of view to bear on the subject.

Simpson's conclusions were based on observations with the Scott expedition in the Antarctic. On September 24, 1911, he observed a 38° fogbow and its double, at temperatures between −15° and −21° F. (−26.1° and −29.4° C.):

The observation proves that the fog was composed of water drops having a radius smaller than 0.025 mm., and this with a temperature of −21° F. (−29° C.). Support is lent to this conclusion by the observation that the hair of sweaters and fur bags became covered with hoarfrost, which is a sure sign of supercooled water.

The occurrence of water droplets at such low temperatures was also noted by J. P. Koch in the far interior of Greenland:[30]

Today [June 10] we saw * * * the white rainbow [fogbow] at a temperature of −31° [C,]. The rainbow occurs always in water clouds, never in ice clouds, so we knew, therefore, that we here had to do with water at −31°. It is naturally possible that the fog cloud had a higher temperature than the air on the ground, though at any rate it could not have been over −18° [the highest recent temperature] * * *. [June 11, longitude 42° 53′ W.] We have again seen to-day the white rainbow, this time at −33.4°. This record for undercooled water will be hard to break.

12 June, 2 a. m., camp site, 42° 53′. Again the white rainbow is there, this time at −34.5°. The record has been broken earlier than I expected. (Trans. by C. F. B.)

While Simpson's and Koch's observations give us temperatures for liquid droplets lower than any previously observed, clouds of liquid droplets as low as −20° to −22° C. (−4 to −8° F.) had been observed in 1893 by A. Berson in a balloon.[31]

On Ben Nevis, fogbows, indicative of liquid droplets, "have been observed at all temperatures."[32] Water has been supercooled to −80° C.[33]

Simpson says:

It is now generally admitted that while halos are caused by the refraction and reflection of ice crystals, coronæ are due to diffraction effects of either small drops of water or thin ice needles. From certain observations made in the Anarctic I was led to doubt the possibility of ice crystals ever forming diffraction effects * * *.

Pernter's reasons for believing that coronæ are produced by ice crystals may be summed up in the three following statements:

(*a*) Coronæ are seen on clouds having temperatures much below the freezing point.

(*b*) The most beautiful coronæ appear on light white cirro-cumulus or fine cirro-stratus clouds; and these clouds are always composed of ice crystals.

(*c*) Halos and coronæ have been observed at the same time; and as halos are a sure sign of ice crystals the coronæ must, therefore, be formed in ice clouds.

Simpson made the following points: (1) It was not necessary to suppose that very cold clouds must be of ice spicules, for he had observed a fog of liquid droplets at a temperature of −15 to −21° F. (2) Halos and coronas, he claimed, were not to be seen in the same cloud at the same time, notwithstanding entries of both at the same observation. (3) The tendency of spicules to fall with their long axes horizontal should make any coronas formed by them brighter above and below the sun or moon than on the sides. (4) The diverse arrangement of spicules should so weaken their diffracted light as to make the coronas caused by them so faint as not to be noticeable. (5) An explanation of iridescence as a phenomenon not always caused in the same manner as coronas is unnecessary.

Humphreys[34] accepts Simpson's treatment with due caution, and does not touch on Pernter's elaborate discussion. Fujiwhara and Nakano,[35] however, review McConnel's, Pernter's, and Simpson's explanations and concludes that while the Japanese studies are not fatal to the ice-cloud theory, "the water-cloud theory of Doctor Simpson is correct so far as supercooling can take place.

[24] G. Johnstone Stoney, On the cause of iridescence in clouds, *Phil. Mag.*, 5th ser., 24: 87–92, 1887. Repr. from *Sci. Trans. Roy. Soc., Dublin*, 2nd ser., 3:637 fig, 1887 (fig. 9).

[25] Loc. cit., pp. 422–434.

[26] Some presented and discussed in *Nature*, Apr. 7, 1887, 35:533, before his extended discussion in *Phil. Mag.*, loc. cit., 1887, 1889, 1890.

[27] McConnel, loc. cit., 1887, p. 424.

[28] J. M. Pernter, Meteorologische Optik, vol. 3, pp. 449–456. Wien & Leipzig, 1906.

[29] G. C. Simpson, Coronae and iridescent clouds, *Quar. Jour., Roy. Met'l. Soc.*, Oct., 1912, 38:291–301, 3 figs.

[30] J. P. Koch, Durch die weisse Wüste. Die dänische Forschungsreise quer durch Nordgrönland, 1912–13. (A. Wegener, translator.) Ref. to pp. 207–209.

[31] R. Süring, Wissenschaftliche Luftfahrten, vol. 2, p. 192, Braunschweig, 1900.

[32] McConnel, op. cit., 1890, p. 168.

[33] E. W. Washburn, An introduction to the principles of physical chemistry, etc., New York, 1915, p. 77.

[34] Op. cit., pp. 534–536.

[35] S. Fujiwhara and H. Nakano, Notes on iridescent clouds, *Jour. of the Meteorological Soc. of Japan*, June, 1920, 39th yr., pp. 1–9, 3 figs.

The theory [Simpson's] is proved by means of numerical calculation of some typical cases from actual observations and by a simple experiment. [The] hemming or crossing nature of iridescent color on clouds, and its preponderating appearance on thin clouds such as Ci.-Cu., A.-Cu., or Fr.-Cu. are explained." Exner has recently answered Simpson's criticisms of some of Pernter's and McConnel's explanations.[36]

Exner replies as follows to all but (5): (1) Even though liquid droplets may exist at low temperatures, there are clouds of ice spicules nevertheless. (2) Observations in Holland in 1918 reported by Van Everdingen [37] include 10 cases of simultaneous halo and corona on the same cloud. "It is therefore apparently certain that coronas also form in ice clouds." (Trans. by C. F. B.) (3) Since halos, which are formed only by ice crystals, occur with equal brightness in all directions from the sun, it is reasonable to suppose that ice-crystal coronas can do so, too. (4) Computations do not sustain Simpson's assumption that the colors would be too weak to be noticeable in diffraction by spicules. Here the matter stands.

Do angular measurements of coronas show ice spicule origin?—Among the 132 careful angular measurements of coronas collected by Kämtz or made at Ben Nevis Obervatory [38] are the dimensions of 56 double, triple, or quadruple coronas. Now Pernter shows mathematically[39] that with nonspicular coronas the second maximum of light outside the central source comes at a distance of only 506/610ths, or about 78 per cent, as far beyond the first maximum as the first maximum is from the luminary, while with spicular diffraction the successive maxima are at equal angular distances outward from the source of light. Unfortunately, this does not necessarily allow the identification of ice-spicule coronas, on the basis of the occurrence of angular radii of second red rings at just double those of the first, for the clouds are not of droplets all the same size within the range of the corona. This is true even if we leave out of consideration the well-known occurrence of horizontal differences which are the cause of irregular and noncircular coronas and of iridescence. Assmann, making measurements on the Brocken,[40] in a quiet cloud layer near the summit, found that the droplets ranged from 0.005 mm. in diameter at the very top of the cloud layer, through 0.008 mm. 10 meters below the top, 0.011 mm. at 30 m. below the top, to 0.013 mm. at the base (80 m. below the top). Braak found a similar range of sizes in clouds.[41]

Assuming that the effect of the upper half of the cloud would be as if the diffraction were by particles 0.009 mm. in diameter, and that of the lower half of the cloud by particles 0.012 mm. in diameter, the following would, in this case, be the sizes of the successive red rings produced:

	°	°	°	°	°
By droplets 0.012 mm. in diameter	4	7	10	13	16
By droplets 0.009 mm. in diameter	5¼	----------	9⅙	13	17
The result would be red rings at	4⅝	[Extinction]	9½	13	Near 17

On account of the greens of the smaller drops falling at the same distance as the reds of the larger ones, these colors would, in this instance, not appear brightly between about 5½ and 8½° from the luminary. It is evident that the corona such as might have been observed on this cloud would have had its second red wing at 202 per cent of the distance of the first, almost exactly the theoretical 200 per cent for ice spicule coronæ instead of the theoretical 178 per cent for a cloud of droplets all the same size, and that the third and fourth rings would have been at successive distances smaller than that between the first and second. If there were a greater diversity in the sizes of the droplets the first maxima of color would generally fall in opposite phase and thus extinguish the color, or leave but a faint diffuse corona, perhaps without a second ring. If the sizes were more nearly alike, say, making first red rings at 4° and 4⅔°, the seconds would be at 7° and 8⅓°, making a good first ring at 4⅓° and a diffuse second one at 7⅝°, or 177 per cent of the distance of the first, practically the theoretical 178 per cent. There would be no third ring.

This rough analysis may explain the peculiarities to be noted in the angular measurements presented in Tables 3 and 4. As it is normal for cloud droplets to differ in size within the same cloud, it is normal for the second ring of double coronas to be between 178 per cent and perhaps 205 per cent of the distance of the first from the sun or moon. As a considerable diversity in sizes will prevent the formation of coronas, it is not surprising that angular distances of second rings larger than 205 per cent of those of the first are not often observed. Furthermore, in the cases of triple and quadruple coronas it is easy to see why there should be a considerable diversity in the angular distances between the successive red rings; extinctions and reinforcements blot out rings where they might be expected and intensify others farther out, a third and a fourth ring, e. g., representing the third and fourth maxima for the smaller droplets and the fourth and fifth for the larger, the second maximum for the larger droplets having been extinguished, as in the example cited. In these measurements there is obviously no assurance that any corona was formed by spicules.

Ice clouds and simultaneous occurrence of halos and coronas.—Even if these observations can not indicate ice-crystal origin of colored coronas, the almost invariably simultaneous occurrence of lunar annuli and halos constitutes practically indisputable proof of the ice-crystal origin of at least this type of corona. Seventeen times in 27 months I have recorded observations of lunar annuli on cirro-stratus clouds. In 14 of these there was a lunar halo at the same time, apparently on the same cirro-stratus cloud in each case. On one of the remaining three there appeared to be a faint halo; on a second, a halo was observed half an hour later; and on the third no halo was noted, probably because the sky was too heavily clouded to make it visible, though possibly because the thunderstorm cirrus in which it formed did not make a halo. Another corona was visible at the same time on lower clouds, and a thunderstorm within hearing distance occupied the northern sky from northwest to northeast. Thus it seems that annuli are rarely observed except on cirro-stratus clouds which have halos, and, therefore, on clouds unquestionably formed of ice crystals. Although it is possible that such a corona may be caused by liquid droplets from the melting of the lower portion of the sheet of falling snow which constitutes cirro-stratus,[42] ice

[36] J. M. Pernter and F. M. Exner, Meteorologische Optik, pp. 488–495, 2d ed. partly reworked by F. M. Exner, Wien and Leipzig, 1922.
[37] Ibid., p. 462.
[38] Cited by Pernter, loc. cit., 1906, pp. 466–468. Also in 2d ed., pp. 504–506.
[39] Ibid., 1st ed., p. 454, figs. 165, 165a; 2d ed., p. 483, figs. 182, 183.
[40] R. Assmann, Microscopische Beobachtung der Wolken-Elemente auf dem Brocken, *Met. Zeitschr.*, Feb., 1885, 2:43–45.
[41] C. Braak, On cloud formation, K. Mag. en Met. Obs. te Batavia, Verh. 10, 1922, pp. 18–27.

[42] C. F. Brooks, in *Mo. Weather Rev.*, June, 1920, 48:333, and *The Met'l Mag.*, May, 1921, 56:95. Also C. K. M. Douglas, *The Met'l Mag.*, Jan., 1921, 55:274, and June, 1921, 56:126–127.

crystals of a size small enough to make droplets of corona-producing size would themselves make a corona, though of smaller radius. Another possibility, the simultaneous occurrence of droplets and crystals at the same level,[43] *though this would produce a corona*, is very unlikely to be the cause of such enduring annuli, for, owing to the lower vapor pressures of ice, water droplets are too unstable in the presence of ice to last long.

Ice coronas on windowpanes.—Whenever windowpanes are covered with a deposit of small drops of dew or with ice plates (frozen dew), flat crystals, or ice spicules, coronas may be seen about the moon, sun, or other light shining through. Such coronas, in the cases of panes covered with ice crystals are, apparently, invariably small and never double, and their colors, while bright, not so pure as those of water-droplet coronas. Except for their colors, owing, presumably, to a homogeneity greater than that found in a cirro-stratus cloud, and to parallel orientations in the same place, these coronas correspond to annuli seen on cirro-stratus clouds.

Direct observation of frosted windowpanes thus upholds the reasonable surmises from annuli seen on cirro-stratus clouds, that ice-crystal clouds can produce small essentially colorless coronas.

Water droplets as the cause of nearly all if not all colored coronas.—The evidence in favor of water droplets being the cause of nearly all, if not of all, colored coronas, and especially of the brilliant coronas and associated iridescence, appears much stronger than that which can be presented for ice-spicule or other ice-crystal origins. Observation of diffraction colors produced by fogs or clouds known by direct observation to be of water droplets indicates that clouds of water droplets do produce brilliant and extensive coronas and iridescence. Fujiwhara and Nakano[44] experimenting with steam fog reported that colors were visible to 45° from the source of light. Lcomotive exhaust fog on a cold sunny day sometimes gives a flash of color immediately before disappearing. On March 8, 1923, I saw this occur at about 40° from the sun. The same effect may be obtained in cool damp weather or in cold weather, when breath fog readily forms, by blowing in the direction of a light, and, better still, by blowing onto a cold windowpane from a distance of a foot or two. Experiences of mountain observers, balloonists, and aviators with glories on clouds of liquid droplets are commonly described, but never (?) a colored corona or glory on a cloud known to be wholly of ice.

Iridescence on clouds of water droplets only.—In view of the marked differences in sizes of cloud particles required in different portions of a cloud in order to produce iridescence, it is likely that only clouds of quickly condensing or evaporating water droplets could have sufficient local homogeneity yet sufficient general heterogeneity to be iridescent. While some coronas may be spicular in origin and others due to hexagonal ice crystals, iridescence probably occurs only on clouds composed at least partly of water droplets. Certainly the most brilliant phases of iridescence are produced only by water clouds. Iridescent clouds are frequently seen to yield a fall of noniridescent snow, which is quite distinct from the mother cloud. Under such conditions the corona and iridescence usually do not last long enough for a sheet of crystals to develop sufficiently to produce a halo, if, indeed, the crystals usually are of a halo making kind. However this may be, I have on three occasions observed iridescence and on eight others a corona without iridescence, simultaneously with halo or parhelion, evidently on a cloud made up largely of liquid droplets and a sheet of snow falling from it. In a number of other instances of simultaneous halo and corona the cirro-stratus cloud of crystals responsible for the halo seems to have been above the clouds causing the corona. This occurrence of cirrus clouds so commonly attached to or growing from iridescent clouds led earlier observers to conclude erroneously that in spite of the rapidity of formation and evaporation, which pointed to water droplets, the iridescent clouds must nevertheless be of ice crystals.

Conclusion on cause of coronas and iridescence.—Since, therefore, (1) iridescence to the greatest limits observed occurs on clouds known or presumed, with greatest confidence, to be of water droplets, (2) liquid clouds occur at low temperatures, (3) angular measurements seem to indicate that coronas occur generally if not quite exclusively on water-droplet clouds, and (4) there appears to be no instance of a colored corona on a cloud known or reasonably presumed to be wholly of ice crystals, it seems justifiable almost without reservation to uphold Simpson in contending that coronas and iridescence occur exclusively on clouds of liquid droplets.[45] All doubt on this score can probably be removed only through careful direct observations from airplanes or airships driven into clouds showing coronas, glories, or iridescence, though a laborious computation or diffraction experiments with suitable artificial spicules would be helpful.

The consequences of this conclusion, pending direct observations to establish or overthrow it, are interesting when considered in conjunction with the relations between temperature and extent of iridescence on fracto-cumulus clouds.

IRIDESCENCE AND CORONAS AS GUIDES TO TEMPERATURE AND, THEREFORE, GENERAL CLOUD HEIGHT

The angular distance to which iridescence may be seen is not only a function of the size of the droplets involved but also one of the brightness of the light and the degree to which white light can be shut out, as with dark glasses. Since the moon, which is one-millionth or less as bright as the sun, can produce visible iridescent colors to a third maximum 11° out, or a second one at 12° from the lighted edge, iridescent colors, per se, are probably strong enough about the sun to be visible to the theoretical limit of 90° if reflected light and sky light were not so strong. Homogeneity in the density of a cloud, usually shown by its apparent smoothness, and homogeneity in the size of droplets over appreciable areas, is essential to the development of the widest angles of visible iridescence. Still another factor is the contrast in the size of droplets between interior and edge of the cloud. This must be sufficient to yield different diffraction colors at the same angular distances from the sun. Furthermore, the cloud must be of sufficient density to make bright diffraction colors. A very thin cloud at a large angular distance diffracts too little of the colored light even to be seen. A thick cloud, however, is not likely to let enough light through to give coloring, or else it reflects so much light that the coloring is obscured.

The temperature at which condensation takes place has an important bearing on the sizes of the droplets and the density of the cloud produced, and therefore, on the

[43] A phenomenon once observed by Douglas, ibid., p. 274.
[44] Loc cit., p. 8.
[45] G. C. Simpson, loc. cit.

extent and brilliance of diffraction colors in the cloud. The lower the temperature the less is the vapor that can be condensed, and, assuming an equal number of nuclei at different temperatures, the smaller are the droplets that can be formed. Thus the cloud formed at low temperature is likely to be of smaller droplets and less dense than one formed at high temperature. Since the extremely small droplets are of little consequence when other sizes predominate, the smaller the size of the majority of droplets the more uniform are the sizes within a cloud, and, therefore, the purer are the colors produced. A cold cloud, thus, is much more favorable to widespread diffraction colors than a warm one. Pernter's conclusion, from observation of more beautiful coronas when the temperature was low, that the clouds causing them were "surely ice clouds" does not seem tenable.[46]

With moderate-sized particles, such as give the first red ring at 3° from the sun, iridescence from the particles of this size would not be expected in brilliant form beyond 11°, the limit of the fourth red ring, while with small particles, such as make the first red ring at 6° from the sun, bright iridescence should occur to 21°. With exceedingly small particles, such as occur in wisps of fracto-cumulus on cold winter days, on which the first red band occurs 10° or perhaps even 12° from the sun, fairly bright diffraction colors are visible to 35° or 40°, the position of the fourth red ring. But portions of the fifth, sixth, and perhaps even the seventh rings are sometimes bright enough to be visible. This extends the visible iridescence to more than half again as great a distance as the bright iridescence. To the extent, therefore, that temperature controls the size of the cloud particles, the angular distance to which diffraction colors are visible may be used as a rough index to the temperature of the cloud, and, through temperature to the height of the cloud.[47]

Iridescence as an indicator of cloud temperatures and altitudes thus becomes *a factor of value in cloud nomenclature.* An examination of Table 9 indicates at once the possibility of generally distinguishing thin alto-stratus and alto-cumulus clouds from cirro-stratus and cirro-cumulus, on the basis of the occurrence of iridescence. If we may judge from the temperatures of iridescent fracto-cumulus clouds (see Table 7), it is only with iridescences extending to 40° or more except on very rapidly forming clouds, that the observer is likely to be viewing clouds having temperatures appropriate to the average heights of cirro-cumulus and cirro-stratus.

[46] Loc. cit., 1st ed., p. 449.

[47] The heights of iridescent clouds was discussed at length a few decades ago. H. Mohn, in an article, Irisirende Wolken (*Met. Zeitschr.*, 1893, 10: 81–97, 240) sought to prove from the late disappearance of sunset light (?) on clouds that were iridescent before sunset that iridescent clouds were at great heights, up to 140 km. O. Jesse, however, said (ibid., pp. 384–385) he had seen iridescent clouds usually at moderate elevations, up to about 7,000 m., and suggested that the late darkening of the clouds observed by Mohn did not represent the actual setting of the sun at their height, but merely the end of more or less intense indirect lighting there. Mohn replied (ibid., p. 460) that the suddenness with which the light left the clouds precluded any lighting less direct than sunlight. Reimann (ibid., 1894, 11: 200) sustained Jesse in saying that his observations showed iridescent clouds to be at no great height. Hildebrandsson, however (ibid., 1895, 12: 71–72), cited another observation of late darkening of a previously iridescent cloud, which under the assumption of direct sunlight indicated a height of 132 km., conforming to Mohn's computations. K. Schips cited (ibid., p. 312) an observation of a very beautiful iridescent cloud that could not have been very high. C. Kassner in summarizing the discussion (ibid., pp. 379–382) suggested that there were two sorts of iridescent clouds, those at moderate heights, and those at very great heights.

If the clouds observed by Mohn and Hildebrandsson had been lighted by the sun directly up to the time when they darkened, then they should have continued to be iridescent till that time, instead of losing their iridescence at about the time of general sunset. It does not take much light to make a cloud look bright in a dark sky, and it is reasonable to suppose that even indirect light might be cut off rather suddenly when the sun ceased to shine on the distant cloud, or whatever it might be that sent the indirect light. There seems no reason for believing that iridescent clouds exist to phenomenal heights.

TABLE 9.—*Average heights of intermediate and upper clouds and the average temperatures at those heights, summer and winter, in the eastern United States and western Europe.*

	United States (Washington, D. C., and Blue Hill, Mass.)				Europe (Trappes, France, and Potsdam, Germany)			
	Summer		Winter		Summer		Winter	
	Average height	Average temperature at average height	Average height	Average temperature at average height	Average height	Average temperature at average height	Average height	Average temperature at average height
	Km.	*° C.*	*Km.*	*° C.*	*Km.*	*° C.*	*Km.*	*° C.*
Ci. St.	W., 10.6	−43	9.5	−49	T., 7.9	−30	5.9	−28
	B. H., 10.1	−40	8.9	−46	P., 8.1	−31	7.6	−41
Ci. Cu.	W., 8.8	−32	7.4	−37	T., 5.8	−15	5.6	−27
	[1] B. H., 8.4	−29	[1] 6.4	−30	P., 5.9	−16	5.4	−25
	B. H., 6.7	−17	6.2	−29				
A. St.	W., 5.8	−11	4.8	−19	T., 3.8	−3	3.8	−15
	B. H., 6.3	−14	4.6	−18	P., 3.3	0	3.0	−9
A. Cu.	W., 5.0	−5	3.8	−13	T., 3.7	−2	4.3	−18
	B. H., 3.8	+2	3.7	−12	P., 3.6	−2	3.4	−12

[1] Heights from H. H. Clayton, Discussion of the cloud observations, etc., Ann. Astr. Obs. Harvard College, vol. 30, pt. 1, p. 340, 1896.

These cloud heights are from the table in W. J. Humphreys', Physics of the air, Philadelphia, 1920, p. 306, copied from J. v. Hann's, Lehrb. d. Meteorologie.

Temperatures for western and central Europe were read from Humphreys, loc. cit. Figure 16, and for the eastern United States, from Gregg, loc. cit., Figure 13.

Herein lies a justification for recommending the use of diffraction colors for distinguishing alto-cumulus from cirro-cumulus and alto-stratus from cirro-stratus. The value of corona observations for this purpose has long been recognized,[48] but they seem to have been applied in observational practice only in Austria-Hungary and Russia,[49] and very recently in the United States.[50] Brooks recommendations of three years ago[51] require minor modifications, in the light of the study of coronas and iridescence discussed in this paper. I quote the essentials, with the changes inserted in brackets [ ]:

Alto-cumulus * * *. In the vicinity of the sun or moon diffraction colors are usually visible * * *.

Alto-stratus * * *. On thin parts of the other (water-droplet) kind, diffraction colors appear in the vicinity of the sun or moon.

Cirro-cumulus * * *. *Small white flakes or tenuous globular masses which* [except rarely] *produce no diffraction colors near the sun or moon* * * *. Ci.-Cu. being composed of ice particles [except in their ephemeral earliest stages], are usually bright, in spite of their tenuity, and do not have the solid appearance characteristic of liquid-droplet, A.-Cu. clouds * * *.

The bracketed modifications introduced should, at least partially, meet the criticisms raised by British meteorologists.[52]

Even in their modified form, however, these suggestions are not in conformity with the usual practice abroad, which, as shown in Table 8, is such as to place cirro-cumulus clouds at an appreciably lower elevation than is customary in America, and which, in consequence of the higher temperature and usual water-droplet composition of such clouds, results in the cirro-cumulus being designated twice as often as alto-cumulus when an iridescent flocculent cloud is observed. Hildebrandsson's observations at Upsala and Arendt's at

[48] Cf. Bericht des Internationalen Meteorologischen Comité und der Internationalen Commission für Woljenforschung, Versammlung zu Upsala, 1894, p. 24.

[49] The matter of coronas in the international cloud definitions and national instructions for observers is discussed in detail by E. Leyst, in Höfe um Sonne und Mond in Russland, *Bull. des Natural. de Moscou*, 1906, No. 182, pp. 9–13.

[50] C. F. Brooks, Cloud nomenclature, *Mo. Weather Rev.*, September, 1920, 48: 516.

[51] Idem.

[52] See *Meteorological Mag.*, 1921, 56: 158–9, 192–3, 219–20; 1922, 57: 183–4, 211; and *Qu. Jour. Roy. Meteor. Soc.*, January, 1923, 49: 3–4.

Potsdam [53] show, respectively, 40 and 50 per cent of the iridescence observations to have been on cirro-cumuli, as against 24 and 20 per cent on alto-cumuli, while Ci., Ci.-St., and Ci.-Cu. grouped together include 58 and 78 per cent of the cases. In my own observations I have credited cirro-cumuli with only 7 per cent, and alto-cumuli with 45, while Ci., Ci.-St., and Ci.-Cu. together comprise only 11 per cent of the total occurrences of iridescence. Cirro-cumulus and cirro-stratus may feature too seldom in these observations, even though I faithfully attempted to keep strictly to the current International definitions.[54]

We should not forget the fundamental basis of height in our International cloud forms. Therefore, as originally intended,[55] all reasonable care should be exercised to reserve the names cirro-stratus and cirro-cumulus for clouds that are distinctly higher than alto-stratus and alto-cumulus. Thinness and small apparent size of elements in the higher clouds are primary criteria, but the thin and small-size initial phases of the lower ones should not lead the observer to misname them with the names of the higher. The occurrence and angular extent of iridescence seems to provide a hitherto unused aid in differentiating what might be called pseudo-cirro-stratus and cirro-cumulus, which are really alto-stratus and alto cumulus ("* * * finer flakes (resembling Ci.-Cu.)"),[56] from the true and higher types.

Conclusion.—The apparent value of the extent of iridescence as a rough index to temperature, and, therefore, to approximate cloud height, should justify, (1) the regular use of dark glasses by observers, (2) the rough angular measurement of the radii of coronas and the extent of iridescence, and (3) the entry of such observations as an essential part of the cloud record. Furthermore, systematic observations of the heights and temperatures of iridescent clouds should be undertaken at aerological stations, in order to establish the degree to which angular extent of iridescence on different cloud types forming at different rates may be used as an indication of cloud temperature and height.

USING WEATHER FORECASTS FOR PREDICTING FOREST-FIRE DANGER

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Three kinds of weather control the fluctuations of forest-fire danger—wet weather, dry weather, and windy weather. Two other conditions also contribute to the fluctuation of fire danger. These are the occurrence of lightning and the activities of man. But neither of these fire-starting agencies is fully effective unless the weather has dried out the forest materials so they are dry enough to burn.

Forest fires can not be started and will not spread unless the forest fuels are dry. Wet weather makes the fuels wet, dry weather makes them inflammable, windy weather fans the flames and makes the fires most difficult to control. If the degree of wetness, dryness, and windiness of the weather can be forecast accurately in time and place, fire danger can likewise be forecast with sufficient accuracy to improve very greatly the efficiency of forest-fire detection and suppression. The purpose of the present article is to illustrate some of the detailed procedures involved in the process of translating weather forecasts into fire-danger forecasts for the conifer timber types of northern Idaho and western Montana.

[53] Arendt, op. cit., p. 223.
[54] International Cloud Atlas, Paris, 1910.
[55] Cf. Brooks, op. cit.
[56] International Cloud Atlas, Paris, 1910. Part of designation of alto-cumulus.

Investigations of the relation of weather to fire danger were initiated in this region by the Priest River Forest Experiment Station in 1916. These first researches were largely devoted to the compilation and comparison of records of weather and forest fires. The report, "Climate and Forest Fires in Montana and Northern Idaho, 1909 to 1919,"[1] by Larsen and Delavan, gives specific data on both weather and fire fluctuations. The present object of fire studies, however, is to make available to the fire-fighting organization all possible information concerning present and probable fire danger so that that organization may expand to meet increasing danger and contract to save unnecessary expense whenever possible.

A forecast of several days of hot, dry weather does not always mean a certain degree of fire danger in this region. The effect of that hot, dry weather depends on how wet the fuels were to begin with. If it has rained recently, a week or more of drying weather may be required before extreme danger will result. Likewise, following a drought, the forecast may be for a period of high humidity, or rain, and the effect will depend on how dry the fuels were to begin with, as well as on how high the humidity may be or how much rain may fall. Before weather forecasts can be used accurately in determining what protective action should be taken, it is necessary to know the prevailing moisture contents of the various fuels.

Studies at the Priest River Forest Experiment Station in northern Idaho have shown that the top layer of duff (decaying leaves and twigs covering the mineral soil) responds to weather changes about as the average of all the combustible forest materials, from moss, weeds, and twigs, to slash and the outside wood on windfalls and snags. The finer and lighter of these fuels pick up and lose moisture rapidly; the heavier fuels, such as branchwood, etc., respond more slowly. The top layer of duff seems to be a reliable criterion of the average response.

An instrument for measuring the prevailing moisture content in that top layer of duff, called a duff hygrometer, has been invented by the U. S. Forest Products Laboratory and the Priest River Station. Numerous tests of the inflammability of duff in relation to its moisture content have permitted the delineation of six zones of inflammability—none, very low, low, medium, high, and extreme. By this means it is possible to apply weather forecasts to a reliable base and so obtain a translation into terms of fire danger. Past practice has shown that such a translation can not be made with sufficient accuracy without such a base to build on.

During the past fire season (1924) three duff hygrometers were used to measure prevailing duff moisture contents on three different sites in the vicinity of the Priest River Forest Experiment Station in northern Idaho. These three sites may be termed, (1) moist site, a fully timbered northwest slope; (2) medium site, a partially cut-over knoll top; (3) dry site, a clean-cut, fully exposed flat. Figure 1 shows the fluctuations of moisture content recorded, also the various zones of inflammability, as previously described.

As might be expected, these three sites, all within a circle less than a mile in diameter, generally exhibited very different degrees of fire danger, the fully timbered station usually showing the most moisture, the clean-cut area the least, and the partially cut area an intermediate amount. Table 1 shows the percentage of time during which each site experienced the various degrees of inflammability.

[1] Mo. WEATHER REV., Feb., 1922, 50: 55-68.